Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

CANMET

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

SECTIONING TESTS ON SYSCO/CNR Cr-Cb PREMIUM RAILS

D.E. PARSONS, D.A. MUNRO and J. NG-YELIM

METALLURGY and ENGINEERING & METAL PHYSICS SECTIONS

MAY 1981

This document is an unedited internal report prepared primarily for discussion and internal reporting purposes. It does not represent a final expression of the opinion of the Canada Centre for Mineral and Energy Technology (CANMET)

Ce document est un rapport interne non révisé rédigé principalement à des fins de discussion et de rapport interne. Il ne constitue pas l'expression définitive de l'opinion du Centre canadien de la technologie des minéraux et de l'énergie (CANMET)

MINERALS RESEARCH PROGRAM

PHYSICAL METALLURGY RESEARCH LABORATORIES

REPORT: MRP/PMRL 81-17(TR)

47 pp

MICROMEDIA

PHYSICAL METALLURGY RESEARCH LABORATORIES
REPORT MRP/PMRL 81-17 (TR)

SECTIONING TESTS ON SYSCO/CNR Cr-Cb PREMIUM RAILS

by

D.E. Parsons, D.A. Munro and J.Ng-Yelim

ABSTRACT

Nine Cr-Cb (1979) rail samples were metallurgically examined and four of the nine were sectioned and tested in detail to determine their mechanical properties including static and dynamic fracture toughness. The 1979 samples were compared with three 1980 Cr-Cb rails and a 1973 Cr-Cb prototype rail previously examined (1,2,9).

The mechanical properties of the 1979 rails and the 1980 rails were similar and closely resembled the 1973 prototype. The fracture toughness of the 1979 samples, however, was slightly lower than either the 1973 prototype or some other types of premium rail with similar strength levels. The average pearlite interlamellar cementite spacing, which ranged from 0.12-0.155 μm (1200 to 1550 Å) in the Cr-Cb rail samples, was coarser than that in some other types of as-rolled, wear-resistant rail.

Several possible methods of obtaining an increase in fracture toughness and a reduction of interlamellar spacing, which would correspond to an increase in 0.2% yield strength (YS) are discussed (3,4).

INTRODUCTION

Nine samples of 1979 Cr-Cb rails were supplied by Sysco and CNR to PMRL, CANMET, Energy, Mines and Resources Canada, for heat treatment experiments. Four samples (from four heats) were supplied by CNR in 60 cm lengths and five samples (from five heats) were supplied by Sysco as 30 cm lengths.

In addition to the heat treatment experiments, supplementary work involving metallurgical examination and the evaluation of mechanical properties was done on the nine samples, in the as-received condition to:

(i) compare with similar data from heat treated specimens and,

(ii) compare the results with a prototype Cr-Cb rail examined in 1973 and with three samples of 1980 Cr-Cb rails.

The results of the supplementary work are described in this report.

EXPERIMENTAL PROCEDURE

Three transverse sections from each of the nine heats were cut out and surface ground to obtain S-prints, metallographic samples and samples for spectrochemical analysis. Figures 1 and 2 illustrate the S-printed transverse sections.

A more detailed examination was made of four samples from heats 39406 (06), 48480 (80), 48791 (12) and 48833-4C (04). The procedures used are listed in Table 1. These samples were sectioned to provide longitudinal (head, web and base) Hounsfield tensile bars; WOL fracture-toughness test bars from the head, head-web junction and base (5); Charpy V-notch and Charpy unnotched (radiussed) impact bars and 2.5 cm diam, 7.6 cm long, end-quenched, hardenability test bars. The head and head-web WOL bars were notched and fatigue-precracked transverse to the length of the rail, whereas the base samples were given longitudinal precracks. Charpy V-notch bars were also fatigue-precracked to obtain dynamic fracture toughness values.

Figure 3 shows the location of the Hounsfield tensile and WOL test bars. Figure 4 shows the location of the Charpy V, Charpy unnotched, and hardenability test bars (J-bars) for samples (06), (80), (12) and (04).

The as-rolled, prior austenite grain sizes (6), were obtained by aqueous picric acid etching and were confirmed by vacuum etching.

EXPERIMENTAL RESULTS

Table 2 lists the chemical composition of the heats showing both the mill analyses and a PMRL (recheck) spectrochemical analysis. The 1973 prototype (vacuum-degassed) heat, 14590 (1)-A, was similar to the 1979-1980 heats (containing less than 0.005% Al) and all were within the composition range for Cr-Cb rails. Table 2 also lists the ASTM E112 austenite grain sizes, the Grossmann "D_i" value calculated from chemical composition and the as-rolled hardness for each sample.

Results from three 1980 samples (2) and from the prototype heat, 14590 (1973) (1), are also included for comparison with the nine test heats in the various tables.

Hardness results from the head, web and base positions in the nine (1979) rails and the 1973 prototype are listed in Table 3. Range and average results are shown. It will be noted that, although samples (20), (27) and (28) were softer than average, the 1979 samples resembled the prototype.

Table 4 lists the average Hounsfield tensile results, of the head, web and base in samples (06), (80), (12) and (04). The web samples are slightly stronger than the head and base samples, but the average tensile results are similar to those of the prototype having a 0.2% tensile YS of about 760 MPa (110 ksi).

Tables 5 and 6, respectively, list the results of unnotched (radiussed) Charpy and Charpy V-notch impact tests made in the temperature range 22°C to -40°C. The unnotched Charpy results at -18°C and -40°C were slightly higher for sample (04) and lower for samples (06), (80) and (12) than the 1973 prototype. The Charpy V-notch results for all samples were at the lower shelf energy which is in the range 2 to 3 J at -40°C and 3 to 4 J at 22°C.

Table 7 lists the results of static fracture toughness (K_{Ic}) tests at 22°C made on four of the nine 1979 heats, on one strand-cast (1980) heat (49078-CIA), and on a vacuum-degassed (1973) prototype heat, 14590.

Similarly, Table 8 lists K_Q and K_{max} fracture toughness results for tests made at -50°C.

Table 9 lists dynamic fracture toughness results and Table 10 lists K_{ID} results for other types of premium rail (7).

Table 11 compares Jominy end-quench (J-bar) results for the four heats (06), (80), (12) and (04) with results for the (1973) prototype heat 14590.

Table 12 gives austenite grain sizes determined according to ASTEM E112.

While Table 13 contains the average and the minimum pearlite interlamellar spacings in the Cr-Cb rails, as observed by electron microscope examination of 2-stage carbon extraction replicas. Some Cb compound particles were exceptionally large as illustrated in Fig. 19.

METALLOGRAPHY

Inclusion Content

Figures 3 and 4 illustrate the distribution of sulphide inclusions in the 1979 Cr-Cb rail samples as recorded by the S-printing of ground transverse sections. The oxide inclusion content was low; no Al_2O_3 inclusions were observed. Sample 80 had a higher than average Si content but unlike sample 2, (1980) did not contain an unusual quantity of silicate inclusions. The sulphide inclusions were elongated by rolling. Samples 1, 2, and 3 (1980) contained higher than average P or Si contents. Sample 2 contained both a high silicon content and large silicate inclusions.

Hardness Gradients (Transverse Sections)

Figure 5 shows the hardness gradient in the head, web and base regions of each sample of rail section. (The results are summarized in Table 3).

Microstructure

Figures 6 to 13 inclusive, illustrate the pearlitic microstructure of the rail-head 5 mm from the head-corner of each rail. Series (a) is at a magnification of 100; Series (b) at a magnification of 500. The ASTM E112 austenite grain size grid is superimposed on the photographs. The prior austenite grain and pearlite colonies are shown after etching with aqueous picric solution. (The peralite is sufficiently fine that it is not resolved at X500.) (Sample (88), heat 48488, is not included, but it resembles sample (80), heat 48480.)

Dynamic fracture toughness charts

Figure 14 illustrates the dynamic fracture-toughness load-time curves of specimens taken from the head, web and base of sample (06). In Fig. 15

traces are also shown from pre-cracked Charpy V-notch bars cut from the base or head positions of the other three samples, (12), (80) and (04). The K_{Id} results pertaining to Figs. 14 and 15 are summarized in Table 9.

Electron microscope examination

Two-stage carbon extraction replicas of eight Cr-Cb rail samples were prepared and examined by electron microscopy. Table 13 lists the average and the minimum interlamellar spacings. Average spacings ranged from 0.12 μm (1200 A) to 0.155 μm (1550 A). (The optical microstructure of the 1973 prototype sample is illustrated in Fig. 16).

Figure 17 is a micrograph showing an area (sample (04)) without large Cb particles, Figs. 18 and 19 (samples (80) and (12) respectively) show areas containing large Cb particles. The average interlamellar cementite spacing, Fig. 17, was 0.12 μm (1200 A). Measurement of Cb particle size indicated that:

1. Some fairly large Cb particles were present ranging from 0.1 μm to 0.7 μm (1000-7000 A). Rail samples 39756 (28) and 39762 (27), which were not considered representative of Cr-Cb rails, contained some coarse Cb particles ranging from 0.2 μm to 1.0 μm (2000-10000 A).
2. Cb particles, when present, appeared randomly within the rail microstructures, but were never observed along grain boundaries. Typical particles are shown in Figs. 18 and 19.

SUMMARY OF OBSERVATIONS

1. The non-degassed 1979 Cr-Cb rails contained less than 0.005% Al with 0.04% to 0.13% Cb and had an austenite grain size of ASTM No. 4-6 whereas the vacuum-degassed 1973 prototype rail (heat 14590) with the same Al and 0.047% Cb had a slightly finer austenite grain size of ASTM No. 6-8.
2. The "D_1" hardenability of the four 1979 Cr-Cb rails was slightly higher than that of the prototype but their J-bar hardness and tensile strengths were similar, and their pearlite spacings ranged from 0.12-0.1375 μm (1200-1375 A). Samples (20), (27) and (28), having the lowest D_1 values, were softer than the R_c37 average for Cu-Cb rails and therefore are not considered to be representative of Cr-Cb rails.
3. The average pearlite interlamellar spacing in all Cr-Cb rail samples of 0.12-0.155 μm (1200-1550 A) was coarser than observed in Steelton or Cr-Mo rails, the latter having average spacings of 0.095-0.123 μm (950-1230 A).

4. The static fracture toughness, K_Q and K_{max}, for 1979 Cr-Cb rails was in the range of 24-34 MPa.$m^{1/2}$ at 22°C, Table 7(a). These values are similar to the values for the 1980 Cr-Cb rails, Table 7(b), the Mn-V (1965) and the 1% Cr (BSC) samples previously tested. They are considerably lower than those of some other premium rails, Table 7(c), (7). Similarly, the dynamic fracture toughness, K_{Id}, of the Cr-Cb rails (25 MPa.$m^{1/2}$), while comparable with Mn-V rails, was lower than for several other types of premium rail, as listed in Tables 9 and 10 - viz: 23-27 MPa.$m^{1/2}$ for Cr-Cb rails, vs., 32-38 MPa.$m^{1/2}$ for Cr-Mo and Steelton oil-quenched, and tempered C-Mn rails.

5. The Cr-Cb railheads, as-rolled, developed maximum hardness to a depth of about 9.5 mm from the rail-head surface, falling to a minimum hardness at the centre of the head (Figs. 5 to 13). Samples (20), (27) and (28) gave low head-hardness values of Rc 29-34. The remaining six samples and the three (1980) samples developed head hardnesses of Rc 34-37, except for sample 88 which had a maximum surface hardness of Rc 40 and an average hardness of Rc 37. [The 1973 prototype sample had a hardness range of Rc 32-38 and an average hardness of Rc 37 corresponding to a 0.2% YS range of 793-814 MPa (115-118 ksi).] (8).

6. The four (1979) samples (06), (80), (12) and (04) gave 0.2% YS values of about 758 MPa (110 ksi) in the railheads, and were similar to the prototype rail. Samples (20), (27) and (28) were not representative of Cr-Cb rail and were not tested.

7. Three heats had average phosphorus contents of 0.04%; four heats had silicon contents in the 0.6-0.7% range. In one of the 1980 samples, No. 2, the high silicon content was also associated with the presence of large silicate inclusions.

8. The quantity and distribution of sulphide inclusions, Figs. 3 and 4, appeared to be normal, as indicated by metallographic examination and S-prints.

9. The Charpy unnotched (radiussed) impact results for the 1973 prototype rail: 156 J at 22°C; 123 J at -18°C; and 19 J at -40°C, were only slightly higher (at -40°C) than average values for the 1979 samples (06), (80), (12) and (04).

10. The Charpy V-notch results for Cr-Cb rails were all very low 1-3 J at temperatures of 22°C to -40°C, again similar to the prototype rail.

DISCUSSION OF RESULTS

The Sysco samples examined were submitted to PMRL primarily as stock for reheat-treatment experiments and for this reason, the SYSCO samples are not all representative of Cr-Cb rail entering service - e.g., samples No. (20), (27) and (28) were exceptionally soft, whereas the four CNR samples (06), (09), (80) and (88) had normal as-rolled hardness for Cr-Cb rail.

The fracture toughness results for the nine 1979 rails and the three 1980 rails were similar and slightly lower than the prototype Cr-Cb rail but were considerably lower than some other premium rails, as listed in Table 7(c).

All of the Cr-Cb rails had average interlamellar pearlite spacings of 0.12-0.155 μm (1200-1550 Å) which were coarser than the 0.095-0.11 μm (950-1100 Å) average spacings observed in the Steelton and Cr-Mo rails.

The air-melted Cr-Cb rails contained columbium without aluminum and had an ASTM grain size of Nos. 4 to 6, whereas the vacuum degassed-columbium practice which the 1973 prototype rail steel was made produced a slightly finer austenite grain size (ASTM Nos. 6-8) than the single addition of columbium in the newer rails. This difference in the austenite grain size may explain the slight decrease in fracture toughness and Charpy (unnotched) impact strength between the 1973 and 1979 Cr-Cb rails but does not account for the difference in fracture toughness when comparing Cr-Cb with other premium rails (Tables 7(c) and 10).

Review of all Cr-Cb rail chemical compositions showed:

(i) three heats had a phosphorus content greater than 0.035%. Segregation of phosphorus above the 0.035% level was therefore possible in three heats.

(ii) Four heats contained silicon in the range of 0.60-0.70% - of these, one 1980 sample (No. 2) contained large silicate inclusions. Restriction of silicon to 0.55% maximum is normal for Cr-Cb rails.

Fracture-toughness testing of fatigue-precracked Cr-Cb (WOL) test bars during tension testing at a cross-head speed of 0.5 mm/min is often characterized by a series of weakly-audible ("pop-in") sounds as loading precedes the K_Q and K_{max} points. Under similar precrack and tensile test conditions, loading of Steelton, 1% Cr or Cr-Mo samples proceeds smoothly to fracture without any pop-in, or with a single, measureable, pop-in immediately be-

fore fracture. The significance of this observation is not known, it is possible to speculate that the effect is in some way related to the presence of the coarse Cb-compound particles observed during electron microscope examination of replicas.

A comparison of Charpy V-notched and Charpy unnotched (radiussed) results for 1979 rails at -40°C showed that the unnotched results for the 1973 prototype were slightly higher than for the 1979 rails (19 vs. 12 J at -40°C).

Toughness increases with decreasing austenite grain size. This can be achieved either by reducing the finishing temperature or by fine grain practice. Toughness is also affected by the degree of misorientation of pearlite lamellae between adjacent pearlite colonies and austenite grains (10).

The 0.2% YS increases with decreasing pearlite interlamellar spacing which results from a lower transformation temperature. The effect is achieved by: (i) an increased cooling rate or, (ii) an increased alloy content. Under some conditions, an increase of 0.2% YS can be obtained by the addition of V or Cb, particularly in the weld region. (Any increase of alloy content is limited in practice by its effect in restricting the speed of electric-flash-welding and by an increased tendency to microsegregation with subsequent transformation of enriched austenite areas to martensite or bainite rather than pearlite).

Some reduction of as-rolled austenite grain size may be possible in Cr-Cb rails by reducing soak and finish-rolling temperatures or by combining deoxidation additions to obtain fine-grained steel (ASTM No. 6 or finer) (11).

The 1979 Cr-Cb rails resembled the 1973 prototype rail, (heat 14590), except for their slightly reduced fracture toughness. (Three softer-than-average rail samples, (20), (27) and (28) were not representative of the strength level of commercial rails (as-rolled) and therefore, were, not fracture toughness tested).

CONCLUSIONS

1. The fracture toughness of 1979 Cr-Cb rails was slightly lower than that of a 1973 vacuum-degassed (prototype) Cr-Cb rail and was considerably lower than that of some other types of premium rail. The tensile strength, hardness, and other mechanical properties of 1979 rail were similar to those for the prototype rail.

2. The average pearlite interlamellar spacing of Cr-Cb rails 0.12-0.155 μm (1200-1550 Å) is relatively coarse in comparison with other premium rails, the latter having average spacings of 0.80-1.10 μm (800-1100 Å).
3. The austenite grain size (ASTM Nos. 4-6) for 1979 Cr-Cb rails, containing columbium without aluminum, was slightly coarser than the grain size (ASTM Nos. 6-8) of the 1973 Cr-Cb prototype rail.
4. Excepting the weld regions, columbium appears to be a relatively ineffective strengthener of rail in the as-rolled condition i.e., in the absence of a normalizing or reaustenitizing treatment. In as-rolled rail some columbium occurs as randomly-spaced, large particles.
5. The distribution of sulphide inclusions in all rails was normal and the macro-inclusion content was low, except in one heat where elongated silicate inclusions were observed in the head of a rail. Three heats had phosphorus contents greater than 0.035%. However, their fracture toughness was not reduced below the average of the 1979 rails.

RECOMMENDATIONS

(1) Increasing the fracture toughness levels of Cr-Cb steels to the levels shown in Table 7(c) and Table 10 should be considered. This might be possible by reducing the as-rolled austenite grain size and by fine grain practice (8,11).

(2) Reducing the pearlite interlamellar spacing should be considered. Theoretically, finer pearlite would result if the cooling rate is accelerated or the A_{r3} transformation temperature depressed by alloy addition.

(3) Addition of up to 0.10% V to the Cr-Cb base composition to obtain an increase of 0.2% YS could be contemplated. (Limits for V, Al and Cb contents, added singly, or in combination are given for plate steel in ASTM-A131-Grade EH36, Section 8) (10).

ACKNOWLEDGEMENTS

The authors acknowledge with thanks the assistance of the PMRL, MRL and TSD staff who contributed to this investigation, particularly G. Weatherall, G. Ayers and Mrs. V. Moore of PMRL, and R. Churchill of MRL for their assistance in mechanical testing, fracture-toughness testing, and microprobe and spectrochemical analyses, respectively.

REFERENCES

(1) Parsons, D.E. and Munro, D.A. "Examination of 1980 Cr-Cb rail samples, 1, 2, 3"; Division Report MRP/PMRL 81-4(CF); CANMET, Dept. of Energy, Mines and Resources; 1981.

(2) Parsons, D.E. "Chemical composition and impact transition temperatures of carbon and alloy rail steels (1951-1977)"; Division Report MRP/PMRL 77-4(R); CANMET, Dept. of Energy, Mines and Resources; 1977.

(3) Parsons, D.E., Munro, D.A. and Ng-Yelim, J. "An investigation of 1% Cr and Cr-Cb rail steels with vanadium and nitrogen additions"; Division Report MRP/PMRL 79-5(TR); CANMET, Dept. of Energy, Mines and Resources; 1979.

(4) Marich, S. and Curcio, P. "Development of high-strength alloyed rail steels suitable for heavy duty applications"; Rail Steels - Developments, Processing and Use; Editors Stone/Knupp ASTM STP 644:167-198; Denver, Colorado; 1976.

(5) ASTM E399-74 Standard Method of Test for Plane Strain Fracture Toughness of Metallic Materials; 561-580; ASTM Committee E24.

(6) ASTM E112-63 Estimating the Average Grain Size of Metals; ASTM Std., Part 2, 205-217; 1974.

(7) Parsons, D.E., Paley, Z. and Munro, D.A. "Comparison of 1% Cr premium rails of Canadian and British manufacture"; Appendix F, 62; Division Report MRP/PMRL 78-16(TR); CANMET, Dept. of Energy, Mines and Resources; 1978.

(8) ASTM A131-74 Structural Steel for Ships, published by ASTM, Annual Book of Standards; Part 4, Section 8, 116.

(9) Parsons, D.E. "Some properties of Mn-Nb (Cr-Cb); Cr-Mo and aluminum-deoxidized carbon steel rails"; Division Report MRP/PMRL 76-19(R); CANMET, Dept. of Energy, Mines and Resources; 1976.

(10) Park, Y.J., Bernstein, I.M. "The process of crack initiation and effective grain size for cleavage fracture in pearlitic eutectoid steel"; ASM/AIME Metallurgical Transaction A., Vol 10A, 1653-1664; November 1979.

(11) Coladao, R., Masounave, J., Guérin, G. and Bailon, J.P. "Austenite grain growth in medium and high-carbon steels microalloyed with niobium (columbium)"; Metal Science, 509-516; November 1977.

Table 1. Method of testing samples 06, 80, 12, 04 (1979) Cr-Cb rails.

1. Spectrochemical analysis
2. Hardness gradient, transverse sections, as-rolled
3. S-print of transverse sections
4. Hounsfield tensile tests - head, web and base positions
5. Charpy V-notched and Charpy (radiussed) unnotched impact tests
6. Static fracture-toughness K_{Ic} tests at 22°C and -50°C
7. Dynamic fracture-toughness K_{Id} tests at 22°C
8. Hardenability tests (J-bar, end-quench tests)
9. Determination of austenite grain size - saturated picric and vacuum etch
10. Metallographic examination, optical microscope
11. Electron microscope, replica examination
12. Interlamellar spacing of carbide in pearlite lamellar
13. Location, size and identification of Cb compounds

Table 2. Chemical composition, γ grain size, hardenability (D_1) and average hardness of nine (1979) heats; three (1980) heats; prototype (1973) heat, Cr-Cb rails.

Sample No.	Ref. code	Chemical composition (% wt.)								γ grain size/ ASTM E112	D_1 Grossman	Hardness as-rolled (Av) Rc
		C	Mn	Si	S	P	Cr	Cb	Al			
1979-rails												
39808-20C	(20)	0.67	0.98	0.43	0.017	0.019	0.76	0.050	<0.005	4/6	4.38	30.3
" "	"	0.64	0.94	0.45	0.016	0.015	0.71	0.047	"			
39762-27C	(27)	0.64	0.94	0.45	0.029	0.024	0.76	0.060	"	"	4.21	31.3
" "	"	0.65	0.95	0.49	0.027	0.028	0.71	0.051	"			
39756-28C	(28)	0.67	0.85	0.31	0.025	0.020	0.78	0.130	"	"	3.74	27.0
" "	"	0.67	0.89	0.30	0.024	0.021	0.71	0.125	"			
48791-12B	(12)	0.72	1.12	0.52	0.021	0.024	0.93	0.040	"	"	6.02	36.3
" "	"	0.73	1.17	0.56	0.020	0.029	0.90	0.041	"			
48833-4C	(04)	0.68	1.12	0.54	0.022	0.029	0.94	0.055	"	"	5.65	35.3
" "	"	0.66	1.10	0.57	0.020	0.034	0.90	0.049	"			
39406*	(06)	0.71	1.05	0.56	0.031	0.025	0.87	0.030	"	"	5.55	33.7
"	"	0.71	1.05	0.66	0.034	0.028	0.87	0.052	"			
39409*	(09)	0.68	0.94	0.48	0.023	0.016	0.82	0.040	"	"	4.61	33.3
"	"	0.66	0.96	0.55	0.022	0.021	0.80	0.050	"			
48480*	(80)	0.65	1.16	0.64	0.019	0.036	0.96	0.040	"	"	5.76	35.0
"	"	0.68	1.21	0.73	0.019	0.026	0.95	0.040	"			
48488*	(88)	-	-	-	-	-	-	-	"	"	6.66	36.7
"	"	0.72	1.10	0.70	0.025	0.012	1.01	0.073	"			

Note: The upper value is the PMRL analysis; the lower value is the mill analysis.

1980-rails												
49078-CIA	(1)	0.71	0.92	0.46	0.027	0.040	0.93	0.049	<0.005	4/6	4.98	35.6
48977	(2)	0.70	1.19	0.65	0.018	0.020	1.05	0.036	"	"	7.23	34.3
C17898	(3)	0.68	1.14	0.50	0.022	0.045	0.90	0.029	"	"	5.74	35.5
1973-rail Prototype												
14590**	(A)	0.61	1.00	0.62	0.023	0.014	0.77	0.047	<0.005	6/8	4.72	37.0
14590**	"	0.67	1.09	0.60	0.024	0.012	0.84	0.056	"			

Residual element content Ni < 0.01%; Mo < 0.01%; V < 0.005%; Sn < 0.002%; Cu < 0.02%

*CNR samples.

**Cb-deoxidized, fine-grained, ingot-cast heat 14590, 1973 (4).

Table 3. Hardness (Rc).
Transverse rail sections, nine as-rolled - 1979 Cr-Cb rails and 1973 prototype rail (4).

Position	Rc	06	09	80	88	20	27	28	12	04	1973 A
Head	Range	29/35	30/36	33/37	34/40	30/34	31/34	27/29	34/39	33/37	32/38
"	Average	32	33	34	37	30	32	27	36	34	34
Web	Range	32/36	31/35	34/40	35/39	30/35	32/35	26/29	35/38	35/39	36/38
"	Average	34	33	36	37	29	31	26	37	36	37
Base	Range	33/36	31/36	34/37	34/38	31/36	31/35	27/30	35/38	34/38	34/37
"	Average	35	34	35	36	32	31	28	36	35	35

Samples (20), (27) and (28) are softer than average.
The prototype (1973) heat 14590, sample (A) results are shown at the extreme right.

Table 4. Hounsfield tensile tests Cr-Cb 1979 rails.

Head	06H UTS MPa (ksi)	0.2% YS MPa (ksi)	Elong $4A^{1/2}$ %	RA %	Head	80H UTS MPa (ksi)	0.2% YS MPa (ksi)	Elong $4A^{1/2}$ %	RA %	Head	12H UTS MPa (ksi)	0.2% YS MPa (ksi)	Elong $4A^{1/2}$ %	RA %	Head	04H UTS MPa (ksi)	0.2% YS MPa (ksi)	Elong $4A^{1/2}$ %	RA %
06H1	1103 (160)	745 (108)	10	21	80H1	1145 (166)	772 (112)	12	31	12H1	1186 (172)	793 (115)	10	22	04H1	1179 (171)	752 (109)	13	28
06H2	1124 (163)	779 (113)	11	22	80H2	1103 (160)	745 (108)	11	25	12H2	1110 (161)	738 (107)	-	-	04H2	1158 (168)	752 (109)	12	25
06H3	1089 (158)	738 (107)	9	17	80H3	1145 (166)	779 (113)	13	30						04H3	1158 (168)	765 (111)	11	23
					80H4	1110 (161)	738 (107)	11	27										
Av.	1105 (160)	754 (109)	10	20		1126 (163)	758 (110)	12	28		1148 (167)	765 (111)	10	22		1166 (169)	756 (110)	12	25

Web	06W				Web	80W				Web	12W				Web	04W			
06W1	1158 (168)	793 (115)	11	27	80W1	1193 (173)	834 (121)	11	29	12W1	1207 (175)	820 (119)	8	12	04W1	1276 (185)	924 (134)	12	30
06W2	1158 (168)	814 (118)	12	30	80W2	-	841 (122)	-	-	12W2	1213 (176)	834 (121)	10	20	04W2	1262 (183)	910 (132)	12	30
Av.	1158 (168)	803 (117)	12	29		1193 (173)	838 (122)	11	29		1207 (175)	827 (120)	9	16		1269 (184)	917 (133)	12	30

Base	06B				Base	80B				Base	12B				Base	04B			
06B1	1158 (168)	793 (115)	13	36	80B1	1145 (166)	752 (109)	14	36	12B1	1158 (168)	738 (107)	13	33	04B1	1200 (174)	793 (115)	16	47
06B2 2	1145 (166)	765 (111)	15	40	80B2	1138 (165)	745 (108)	15	42	12B2	1186 (172)	786 (114)	10	25	04B2	1179 (171)	800 (116)	15	44
06B3	1158 (168)	772 (112)	14	38	80B3	1117 (162)	717 (104)	15	44	12B3	1172 (170)	758 (110)	10	26	04B3	1179 (171)	793 (115)	15	43
06B4	1117 (162)	752 (109)	15	41	80B4	1124 (163)	745 (108)	15	42	12B4	1138 (165)	703 (102)	12	30	04B4	1145 (166)	752 (109)	16	48
					80B5	1158 (168)	772 (112)	15	42	12B5	1179 (171)	786 (114)	10	22					
Av.	1145 (166)	771 (112)	14	39		1136 (165)	746 (108)	15	41		1167 (169)	774 (109)	11	27		1176 (171)	785 (114)	16	46

Note: Average tensile results for the 1973 prototype rail were: (169 ksi UTS: 110 ksi 0.2% YS; 16% Elong; 30% RA) (4).

Table 5. Charpy impact results, unnotched (radiussed) bars.

06				80				12				04			
Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)
06H	22	142	(105)	80H1	22	256	(189)	12H1	22	41	(30)	04H	22	256	(189)
-	-	-	-	80H2	22	213	(157)	12H2	22	36	(27)	-	-	-	-
06W	22	137	(101)	80W	22	39	(29)	12W1	22	53	(39)	04W	22	176	(130)
06B	22	240	(177)	80B	22	210	(155)	12B1	22	52	(38)	04B	22	309	(228)
	Av	173	(128)			180	(133)			46	(34)			247	(182)
06H	4	112	(83)	80H1	4	175	(129)	12H	4	82	(60)	04H	4	268	(198)
-	-	-	-	80H2	4	93	(69)	12W	4	17	(13)	-	-	-	-
06W	4	15	(11)	80W	4	24	(18)	12W	4	50	(37)	04W	4	206	(152)
06B	4	22	(16)	80B	4	290	(214)	12B	4	41	(30)	04B	4	261	(193)
	Av	50	(37)			146	(108)			48	(35)			245	(181)
06H	-18	24	(18)	80H	-18	36	(27)	12H	-18	10	(7)	04H	-18	172	(127)
06W	"	26	(19)	80W	"	"	(8)	12W	"	10	(7)	04W	"	31	(23)
06B	"	233	(172)	80B	"	199	(147)	12B	"	127	(94)	04B	"	274	(202)
	Av	94	(70)			82	(61)			49	(36)			159	(117)
06H	-40	10	(7)	80	-40	-	-	12	-40	-	-	04H	-40	14	(10)
06W	"	7	(5)	80	"	-	-	12	"	-	-	04W	"	11	(8)
	Av	9	(6)											13	(9)

Notes:

(1) Similar radiussed bar tests on the 1973 heat 14590 prototype gave energy values of 115 ft-lb at 22°C; 91 ft-lb at -18°C and 14 ft-lb at -40°C (4).

(2) H = head; W = web, B = base.

(3) 1 ft-lb = 1.355818 Joules.

Table 6. Charpy impact results, V-notch test bars.

Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)	Bar No.	Test temp (°C)	Impact energy J	(ft-lb)
06H	22	3	(2.2)	80H	22	4	(3)	12H	22	3	(2.2)	04H	22	3	(2.2)
06W	"	3	(2.2)	80W	"	2.5	(1.8)	12W	"	2.5	(1.8)	04W	"	3	(2.2)
06B	"	3	(2.2)	80B	"	4	(3)	12B	"	3	(2.2)	04B	"	3	(2.2)
	Av	3	(2.2)			3.5	(2.6)			2.8	(2.0)			3	(2.2)
06H	-40	2	(1.5)	80H	-40	3	(2.2)	12H	-40	2	(1.5)	04H	-40	2.5	(1.8)
06W	"	2	(1.5)	80W	"	2	(1.5)	12W	"	2	(1.5)	04W	"	2.5	(1.8)
06B	"	2	(1.5)	80B	"	2	(1.5)	12B	"	3	(2.2)	04B	"	5	(3.7)
	Av	2	(1.5)			2.3	(1.7)			2.3	(1.7)			3.3	(2.4)

Notes:

(1) Prototype values were 1-2 ft-lb at 22°C (4).

(2) H = head; W = web; B = base.

(3) 1 ft-lb = 1.355818 Joules.

Table 7(a). Fracture toughness (K_{Ic}) - 1979 Cr-Cb rail at 22°C.

Bar No.	Test temp (°C)	K_Q		K_{max}		Tensile load P_Q	Tensile load P_{max}	ASTM E399-74 data: fatigue pre-crack length	a	$\frac{a}{W}$	$f\left(\frac{a}{W}\right)$
		$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$	$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$	kgf	kgf	(mm)	(mm)		
06H2	22	32.36	(29.417)	35.72	(32.476)	818	898	3.07	11.79	0.550	11.26
06B2	"	28.08	(25.529)	30.76	(27.961)	764	836	3.00	11.33	0.528	10.47
06B3	"	28.64	(26.038)	31.46	(28.597)	786	864	2.54	11.25	0.525	10.37
	22°C Av	29.69	(26.995)	32.57	(29.611)						
80H2	22	24.07	(21.884)	25.95	(23.594)	582	627	3.35	12.07	0.563	11.78
80W	"	23.58	(21.436)	27.22	(24.746)	618	714	2.84	11.56	0.539	10.86
80L2	"	23.24	(21.123)	27.08	(24.621)	714	832	1.75	10.46	0.488	9.27
	22°C Av	23.63	(21.481)	26.75	(24.320)						
12H2	22	27.41	(24.921)	29.57	(26.879)	868	936	1.52	10.24	0.477	8.99
12W	"	27.71	(25.190)	28.97	(26.340)	895	936	1.37	10.08	0.470	8.81
12L1	"	29.11	(26.462)	30.35	(27.594)	850	886	2.11	10.82	0.505	9.75
	22°C Av	28.08	(25.524)	29.63	(26.938)						
04H2	22	29.86	(27.142)	32.36	(29.420)	623	675	4.19	12.90	0.602	13.65
04W	"	26.77	(24.340)	29.88	(27.168)	900	1005	1.07	9.78	0.456	8.47
04L1	"	28.15	(25.595)	35.83	(32.576)	600	764	4.09	12.80	0.597	13.36
	22°C Av	28.26	(25.692)	32.69	(29.721)						

Table 7(b). Fracture toughness (K_{Ic}) - 1980 Cr-Cb rail sample (No. 1) A-78, strand-cast.

Bar No.	Test temp (°C)	K_Q		K_{max}		Tensile load P_Q	Tensile load P_{max}	ASTM E399-74 data: fatigue pre-crack length	a	$\frac{a}{W}$	$f\left(\frac{a}{W}\right)$
		$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$	$MPa \cdot m$	$(ksi \cdot in.^{1/2})$	kgf	kgf	(mm)	(mm)		
A-78-3	22	28.36	(25.780)	29.98	(27.253)	795	841	2.39	11.10	0.518	10.15
A-78-4	"	27.63	(25.115)	28.45	(25.862)	764	786	2.49	11.20	0.523	10.30
A-78-5	"	28.88	(26.258)	30.14	(27.400)	941	982	1.30	10.00	0.467	8.74
A-78-7	"	27.75	(25.228)	30.90	(28.093)	820	914	2.03	10.74	0.501	9.63
22°C Av		28.15	(25.595)	28.97	(27.152)						

Table 7(c). Fracture toughness (K_{Ic}) 22°C results for prototype Cr-Cb and some other types of rail (4). (New rail).

Type of rail	K_Q		K_{max}		Average hardness railhead Rc	Description
	$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$	$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$		
Cr-Cb (1973) prototype*	30.31	(27.557)	37.55	(34.133)	37	Heat, 14590 (A) (4)
Carbon steel, as-rolled	33.88	(30.797)	43.89	(39.898)	30	Standard 66 kg/m (132 lb/yd)
Carbon steel QT Steelton	45.66	(41.510)	52.86	(48.050)	38	Oil quenched-tempered
Cr-MoI-C5599	42.62	(38.748)	54.38	(49.436)	38	Ingot-cast, Al-killed, pearlitic
1% Cr, 0.7% Mn, ASC	36.24	(32.948)	43.14	(39.216)	35	pearlitic
1% Cr, 1.4% Mn, BSC	27.89	(25.359)	32.46	(29.511)	35	pearlitic
USSR P-65 QT	46.76	(42.513)	50.73	(46.116)	37	Russian, quenched-tempered
Cr-Mo II, 9273B-Z	34.90	(31.727)	38.70	(35.182)	44	Strand-cast, Si-killed, bainitic
Mn-V (1965)	32.65	(29.631)	39.53	(35.940)	34	QNSRL (1965)

*1973 Cr-Cb prototype rail-vacuum degassed, ingot cast.

Table 8(a). Fracture toughness (K_{Ic}) -50°C results for 1979 Cr-Cb rail.

Cr-Cb Sample	Test temp (°C)	K_Q MPa.m$^{1/2}$	K_Q (ksi.in.$^{1/2}$)	K_{max} MPa.m$^{1/2}$	K_{max} (ksi.in.$^{1/2}$)	Tensile load P_Q kgf	Tensile load P_{max} kgf	ASTM E399-74 data: fatigue pre crack length mm	a mm	$\frac{a}{W}$	$f\left(\frac{a}{W}\right)$
06H1	-54	22.35	(20.319)	24.03	(21.843)	454	489	4.32	13.02	0.608	14.00
06H-W	-	-	-	-	-	-	-	-	-	-	-
06B1	-52	26.14	(23.763)	29.08	(26.439)	505	561	4.60	13.31	0.621	14.75
-50°C Av		24.25	(22.041)	26.56	(24.141)						
80H1	-52	21.68	(19.709)	22.88	(20.803)	655	691	1.88	10.59	0.494	9.43
80L1	-53	21.42	(19.476)	23.46	(21.331)	573	627	2.72	11.43	0.533	10.65
80L3	-52	21.55	(19.592)	23.34	(20.305)	561	582	2.90	11.61	0.541	10.93
-50°C Av		21.55	(19.592)	22.89	(20.813)						
12H1	-53	20.64	(18.760)	23.14	(21.039)	486	545	3.51	12.22	0.570	12.08
12L2	-	-	-	-	-	-	-	-	-	-	-
12L3	-53	15.40	(13.998)	15.77	(14.335)	377	386	3.28	11.99	0.559	11.62
-50°C Av		18.02	(16.379)	19.46	(17.689)						
04H1	-53	24.31	(22.104)	25.50	(23.186)	650	682	2.72	11.43	0.533	10.65
04L2	-54	26.58	(24.167)	28.55	(25.957)	859	923	1.37	10.08	0.470	8.81
04L3	-53	27.19	(24.722)	29.73	(27.026)	732	800	2.67	11.38	0.531	10.58
-50°C Av		26.01	(23.644)	27.93	(25.390)						

H = head; W = web; B = base; L = longitudinal precrack in base; otherwise transverse precracks.

Table 8(b). Fracture toughness (K_{Ic}) -50°C results for 1980 Cr-Cb rail (No. 1). A-78, "strand-cast".

A78.1	-51°	23.56	(21.417)	25.12	(22.834)	618	659	2.84	11.56	0.539	10.85
A78.2	-50°	23.23	(21.122)	24.74	(22.490)	632	673	2.62	11.33	0.528	10.47
A78.3	-53°	23.35	(21.228)	24.75	(22.499)	645	684	2.49	11.20	0.523	10.30
	-50°C Av	23.38	(21.256)	24.87	(22.608)						

Table 9. Dynamic (K_{Id})* fracture toughness at 22°C Cr-Cb rails (fatigue-precracked Charpy V-notch bars, W = 10 mm).

Heat	Code ref.	Position	K_{Id}		a	$\frac{a}{W}$	$a^{1/2}$	Y	P_{max}	Energy
			$MPa.m^{1/2}$	$(ksi.in.^{1/2})$	mm	-	in.	-	kg	J
39406	06H	head	25.6	(23.27)	3.94	0.394	0.394	2.06	336	1.0
"	06W	web	26.7	(24.27)	3.90	0.390	0.392	2.05	355	0.3
"	06B	base	25.6	(23.27)	4.14	0.414	0.404	2.13	318	0.7
48480	80B	base	26.6	(24.18)	3.19	0.319	0.354	1.88	427	0.3
48791-12B	12B	base	25.1	(22.82)	4.08	0.408	0.401	2.10	318	0.7
48833-4C	04H	head	23.2	(21.09)	3.95	0.395	0.394	2.06	305	0.5

* $K_{Id} = (38.7\ Ya^{1/2}.\ P_{max})\ 1.1$ $(MPa.^{1/2})$

Table 10. Dynamic fracture toughness (K_{Id}) at 22°C (other types of rail) (2,7).

Heat and description	K_{Id}		a	$\frac{a}{W}$	$a^{1/2}$	Y	P_{max}	Energy	0.2%	YS	Hardness
	$MPa \cdot m^{1/2}$	$(ksi \cdot in.^{1/2})$	mm	-	in.	-	kg	J	MPa	(ksi)	Rc
(18)-9273B, Cr-Mo II	34.8	(31.64)	3.85	0.385	0.389	2.04	468	0.7	965	(140)	44
(17),(38)-C5599 Cr-Mo I	38.2	(34.73)	4.30	0.430	0.411	2.18	454	0.4	827	(120)	39
(38)-9273B, Cr-Mo II	31.5	(28.64)	3.53	0.353	0.373	1.96	459	0.5	965	(140)	44
3220-C-B-Al, as-rolled C	36.7	(33.36)	4.28	0.428	0.411	2.18	436	0.7	552	(80)	30
Carbon QT Steelton G	35.6	(32.36)	3.38	0.338	0.365	1.91	545	0.7	813	(118)	38
Y-38 Mn-V 1965*	25.0	(22.73)	3.03	0.303	0.345	1.85	418	0.4	724	(105)	35

*The K_{Id} result for Mn-V (1965) steel is approximately equal to that for 1979 Cr-Cb rails, Table 9.

Cr-Mo-I-heat C5599 - Al-killed, fine-grained, ingot-cast, pearlitic microstructure (Rc 39).

Cr-Mo-II-heat 9273B - Si-killed, coarse-grained, strand-cast, upper bainite microstructure (Rc 44).

C-B-Al - Al-killed, fine-grained, as-rolled C steel containing Boron (Rc 30).

Steelton - oil-quenched-tempered carbon steel, Bethlehem Steel Co., (Rc 38) (Si-killed).

Y-38 - as-rolled, DOSCO, Mn-V (1965) (Rc 35) (Si-V-killed).

Table 11. End-quench, J-bar hardness (Rc).
Determined experimentally using 2.5 cm diameter, 7.6 cm long J-bars, end-quenched in water after austenitizing 1/2h at 885°C .

J-bars, cut from Cr-Cb rails

Hardness interval		06	80	12	04	14590 1973-prototype
(mm)	(in.)	-	-	-	-	-
1.59	1/16	65	64	66	65	65
3.18	2	"	"	"	"	"
4 .76	3	"	"	"	64	"
6.35	4	"	"	"	65	"
7.94	5	"	"	"	64	"
9.53	6	"	"	"	65	"
11.11	7	"	"	65	"	"
12.70	8	"	"	66	"	"
14.29	9	"	"	65	"	"
15.88	10	64	"	66	"	"
17.46	11	"	"	"	64	"
19.05	12	"	"	"	"	"
20.64	13	"	"	65	64	"
22.23	14	"	"	"	"	64
23.81	15	63	"	"	63	63
25.40	16	62	"	"	"	"
31.75	1 1/4	58	63	63	61	60
38.10	1 1/2	44	63	51	46	47
44.45	1 3/4	40	61	43	40	41
50.80	2	37	44	40	37	38
57.15	2 1/4	35	40	38	36	36
63.50	2 1/2	34	38	37	35	-
69.85	2 3/4	35	38	37	35	-
76.20	3	-	-	-	-	-
"D_i"*		5.55	5.76	6.02	5.65	4.72
Av (Rc) hardness		34	35	36	35	37

*Calculated from chemical composition.

Table 12. Austenite grain size, "as-rolled".

Austenite grain size	1979 Cr-Cb rails									1980 rails			1973 prototype
	06	80	12	04	20	27	28	09	88	1	2	3	A*
Etched 10 s in boiling aqueous 4% picric acid. γG.S.	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	6-8
Vacuum etched 16 h at 675°C (1250°F) γ G.S.	4-6	4-5	4-6	6-7	4-6	5-6	4-7	4-5	-	-	-	-	-
Grossmann "D_1"	5.55	5.76	6.02	5.65	4.38	4.21	3.74	4.61	6.66	4.98	7.23	5.74	4.72
Av. rail hardness (Rc)	34	35	36	35	30	31	27	33	37	36	34	35	37

Notes:
(1)* Sample A, heat 14590, vacuum degassed, Cb-treated.
(2) Samples (12) (88) and (2) gave highest "D_1" calculated hardenability values.
Samples (20) (27) and (28) gave lowest "D_1" calculated hardenability values.
Samples (80) and (12) gave the highest J-bar hardenability of the samples tested.

Table 13. Pearlite interlamellar spacings for Cr-Cb rail samples.

[1μm = 10^4Å]

Heat No.	Reference code	Average observed spacing A (cm^{-8})	Mininum observed spacing A (cm^{-8})
48833-4C	04	1200	915
39808-20C	20	1200	960
48480	80	1200	915
48791-12B	12	1250	850
39406	06	1375	1000
39762	27	1400	1050
39756	28	1550	930
39409	09	1550	850

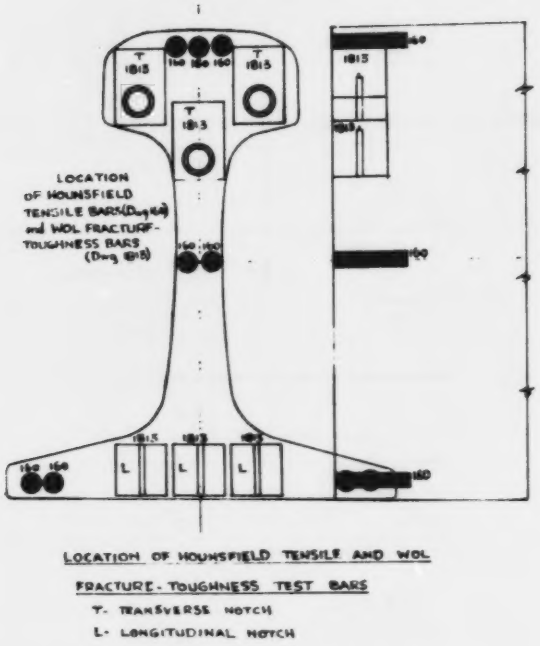


Fig. 1. Location of Hounsfield tensile and WOL fracture-toughness test bars. (neg 4526)

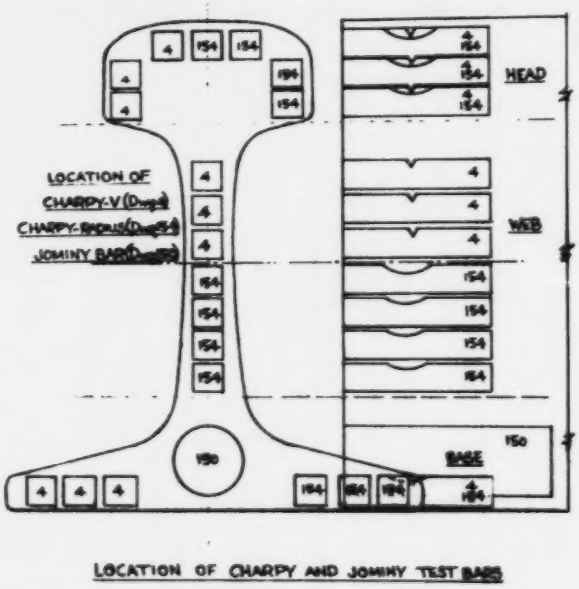
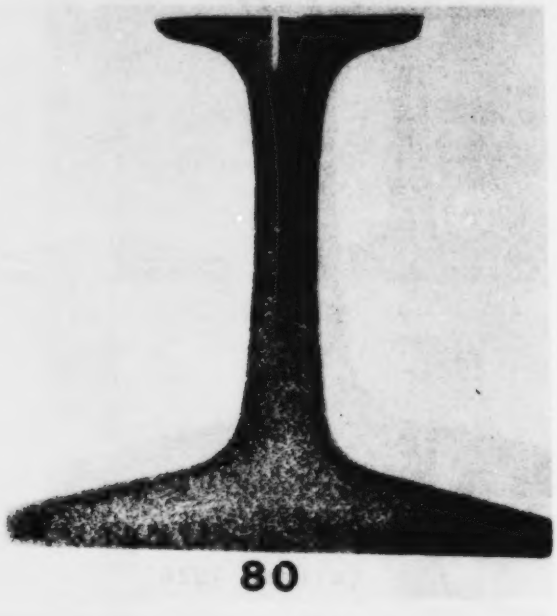


Fig. 2. Location of Jominy test bar and of Charpy V-notched or radiussed Charpy unnotched test bars. (neg 4525)

(a) (neg 4021)



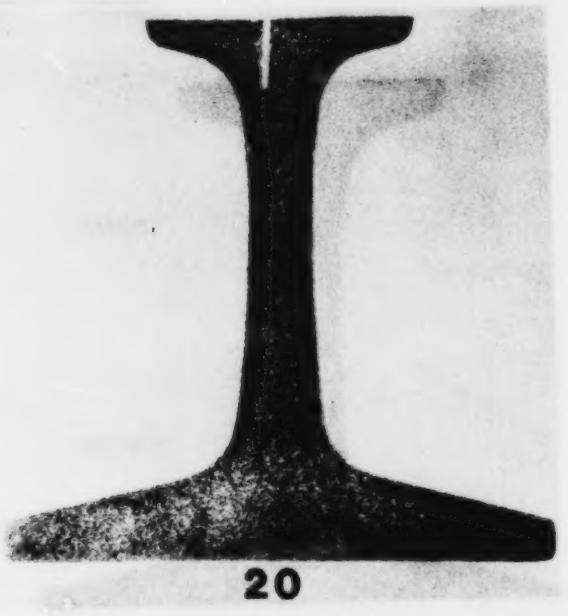
(b) (neg 4025)

(c) (neg 4024)

(c) (neg 4020)

Fig. 3. Sulphur prints, transverse sections, samples 06, 80, 12 and 04 Cr-Cb rails. X1/2.

(a) (neg 4026)

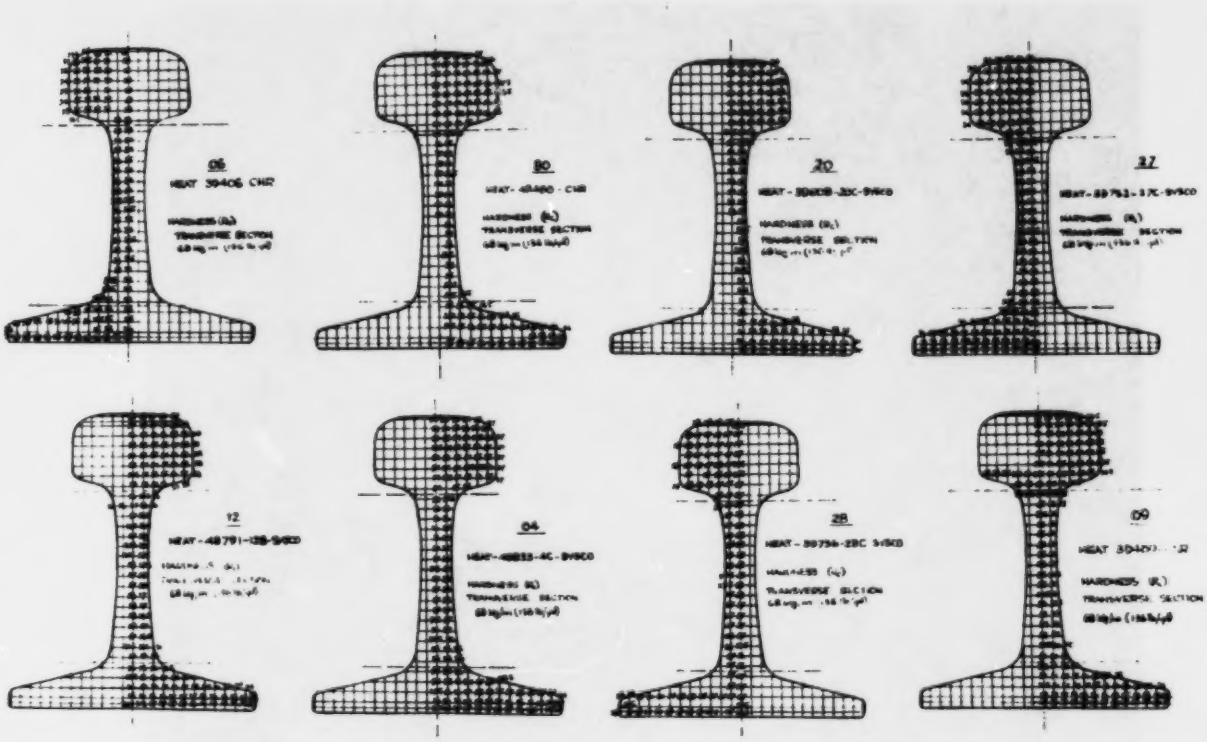


(b) (neg 4023)

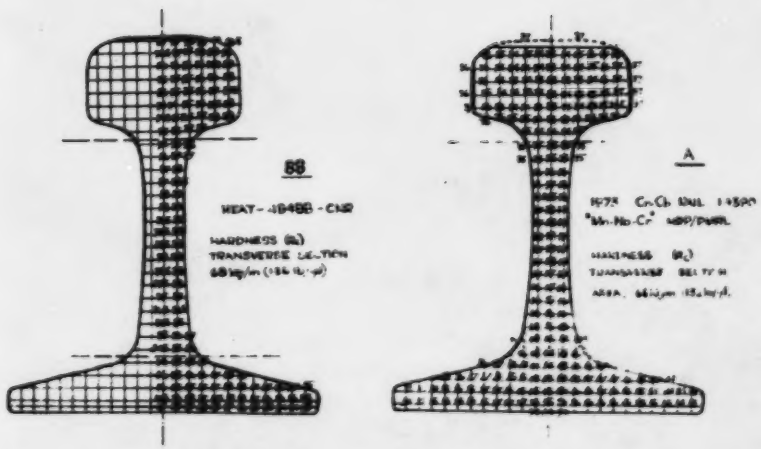
(c) (neg 4019)

(d) (neg 4022)

Fig. 4. Sulphur prints, transverse sections, samples 09, 20, 27 and 28, Cr-Cb rails. X1/2.

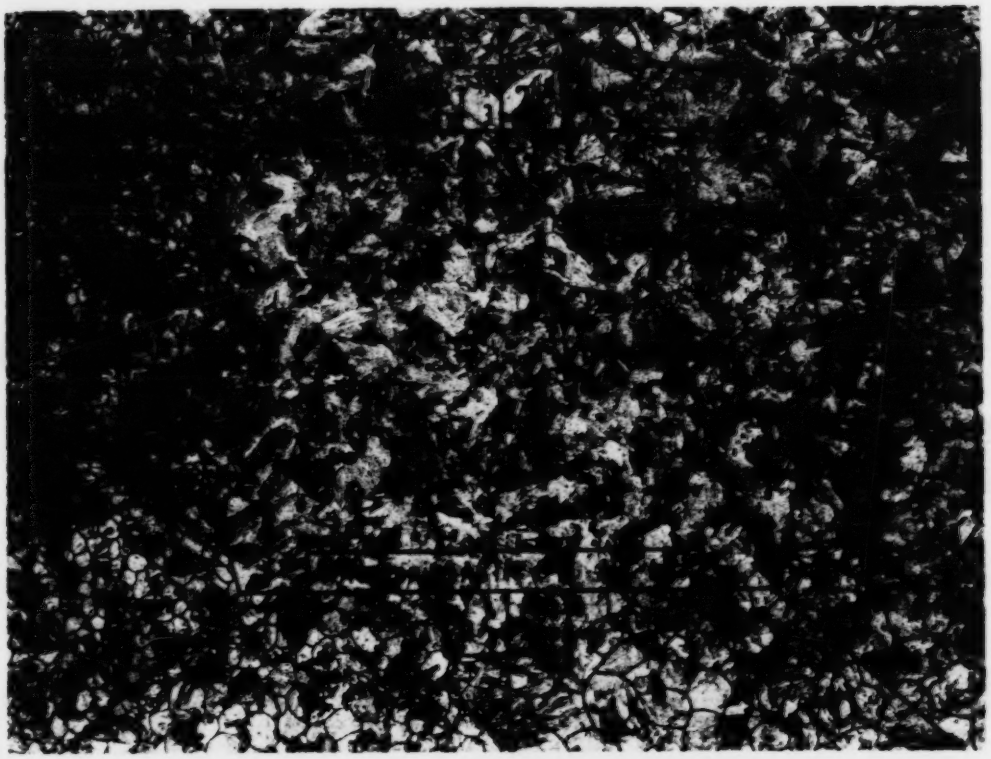


(a) (neg 4522) (b) (neg 4524)

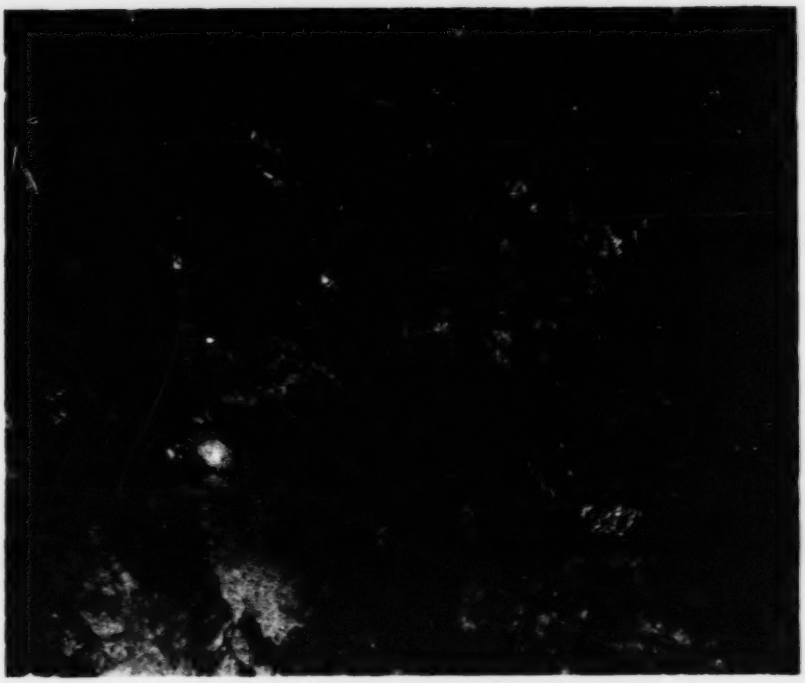


(c) (neg 4523)

Fig. 5. Hardness (Rc) on transverse sections - Cr-Cb rails.

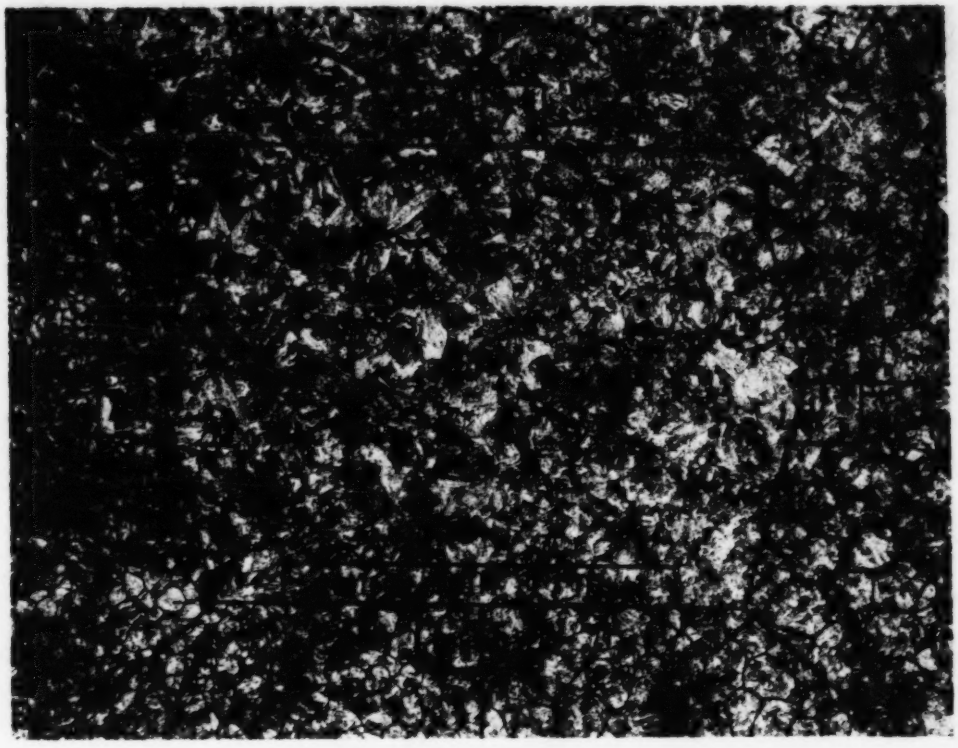


(a) X100. (neg 4481)



(b) Part of same area as (a). X500. (neg 4473)

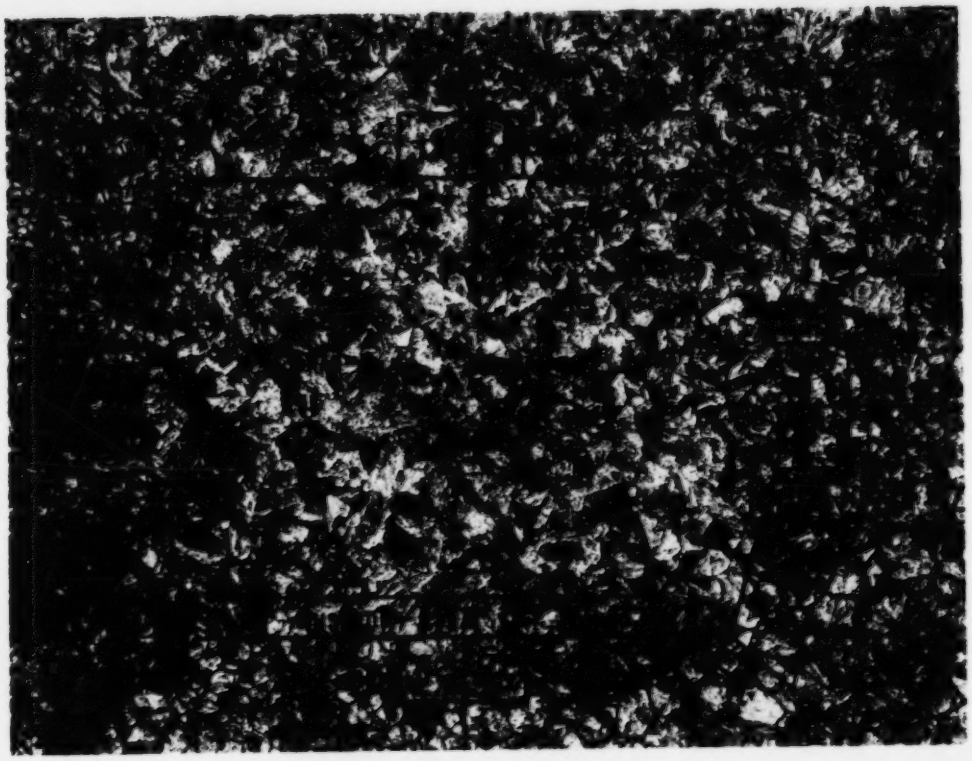
Fig. 6. Sample 06, (heat 39406). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = No. 4-6, (b) illustrates the prior austenite grain boundaries, (Rc32).



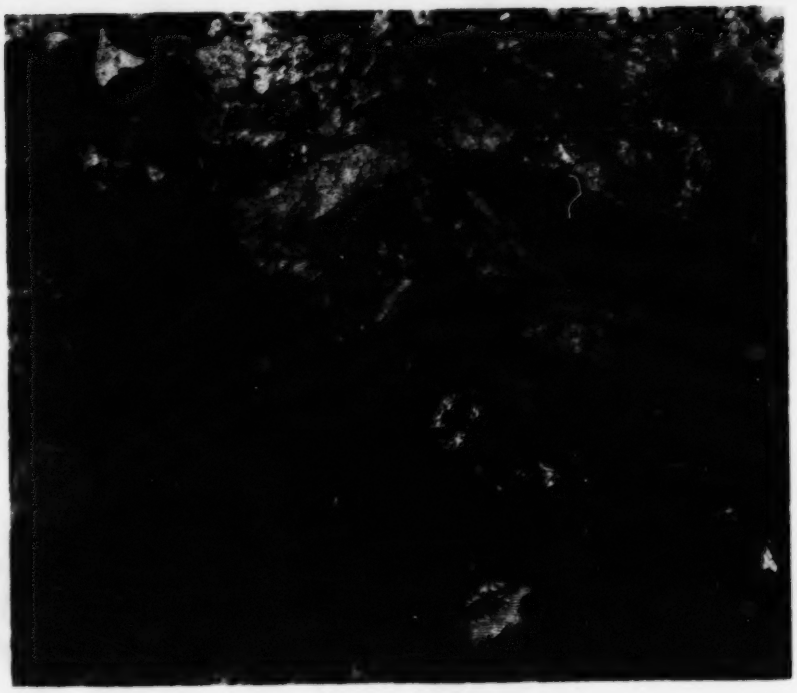
(a) X100. (neg 4482)

(b) Part of same area as(a). X500. (neg 4474)

Fig. 7. Sample 80, (heat 48480). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = No. 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 34).

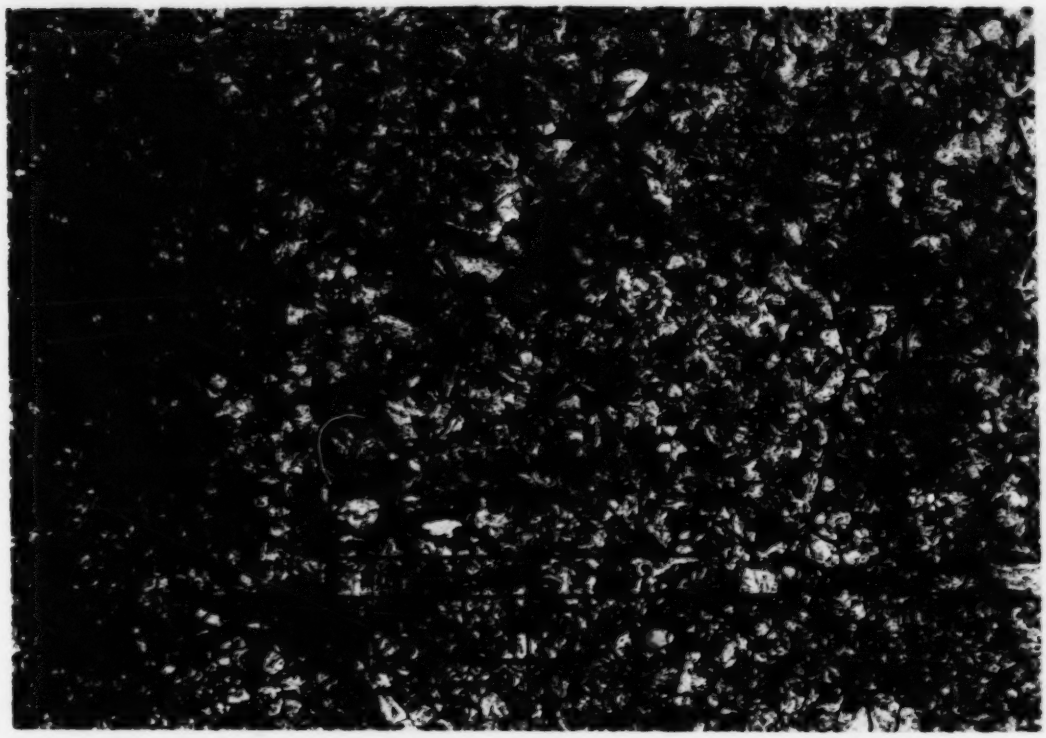


(a) X100. (neg 4483)

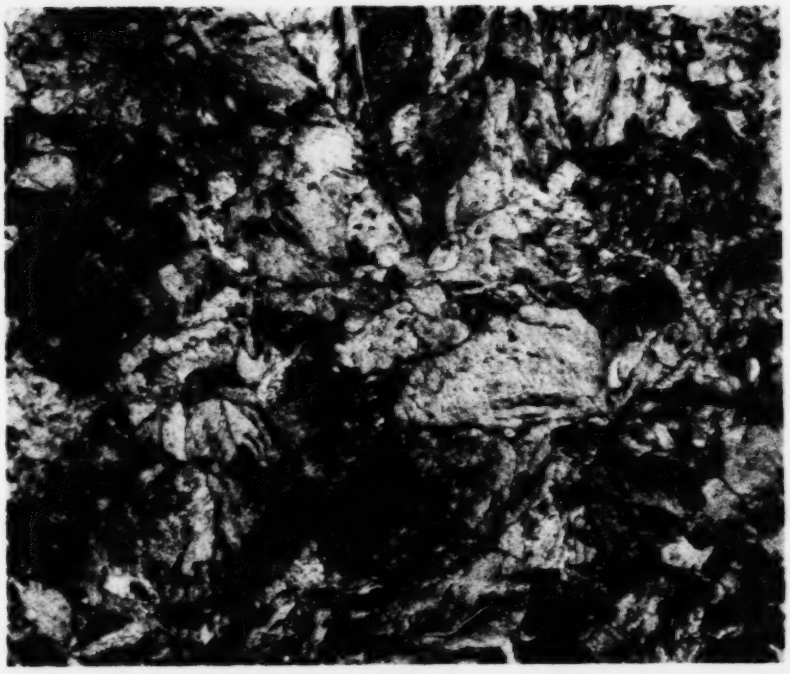


(b) Part of same area as (a). X500. (neg 4475)

Fig. 8. Sample 12, (heat 48791-12B). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = No. 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 36).

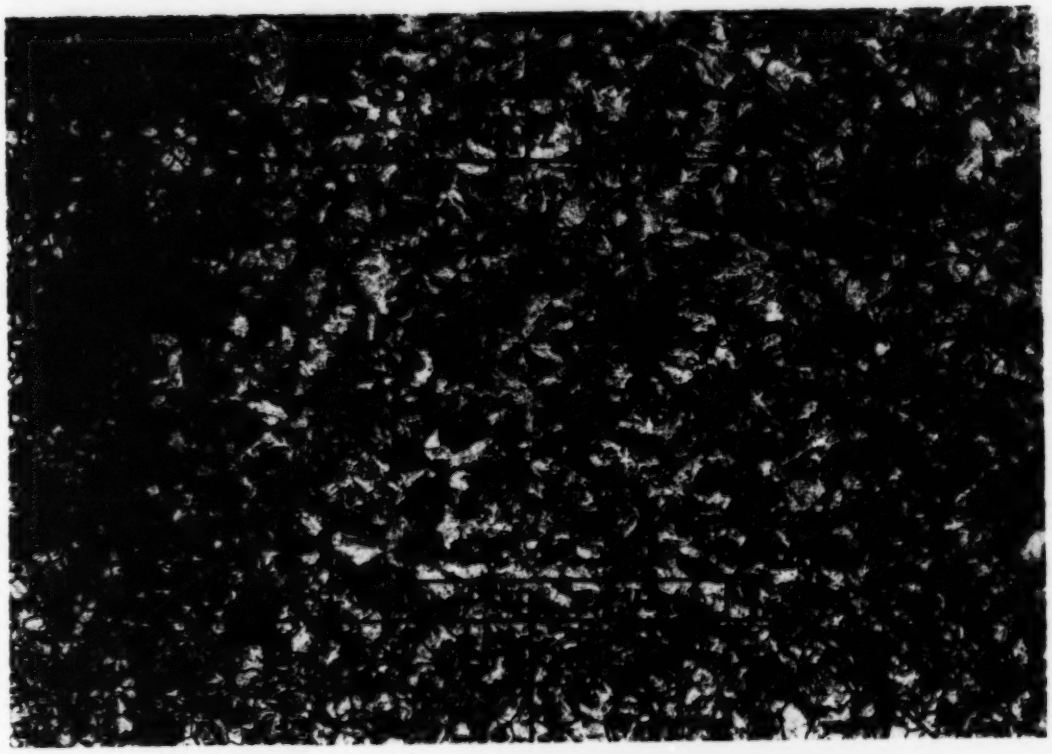


(a) X100. (neg 4484)



(b) Part of same area as (a). X500. (neg 4476)

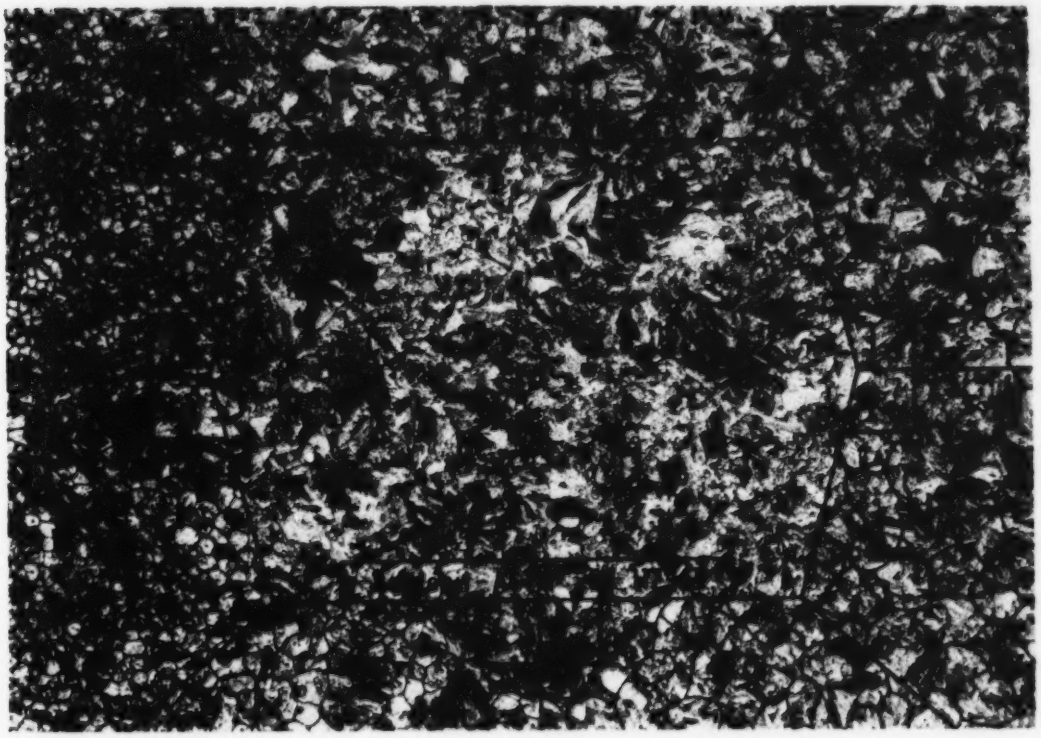
Fig. 9. Sample 04, (heat 48833-4C). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = No. 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 34).



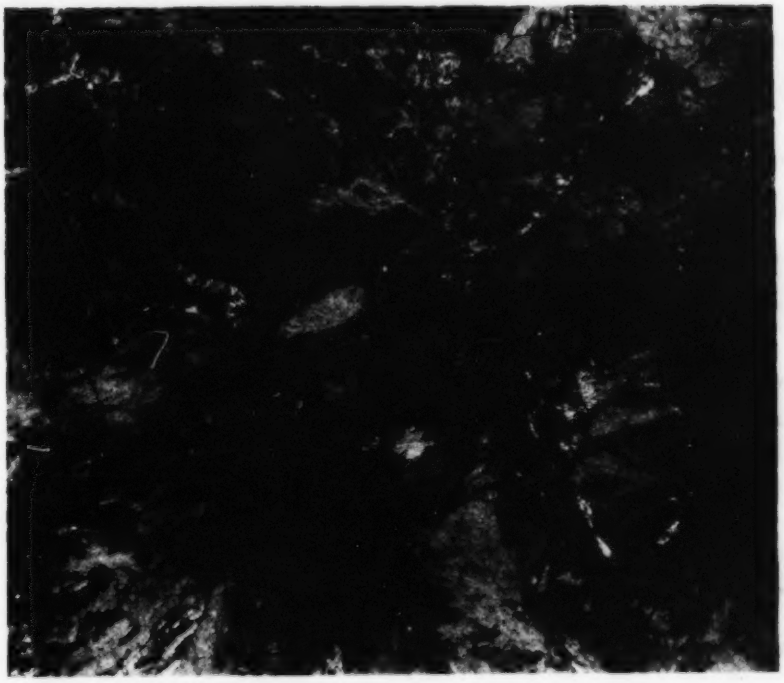
(a) X100. (neg 4485)

(b) Part of same area as (a). X500. (neg 4477)

Fig. 10. Sample 09, (heat 39409). Etched in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = No. 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 33).

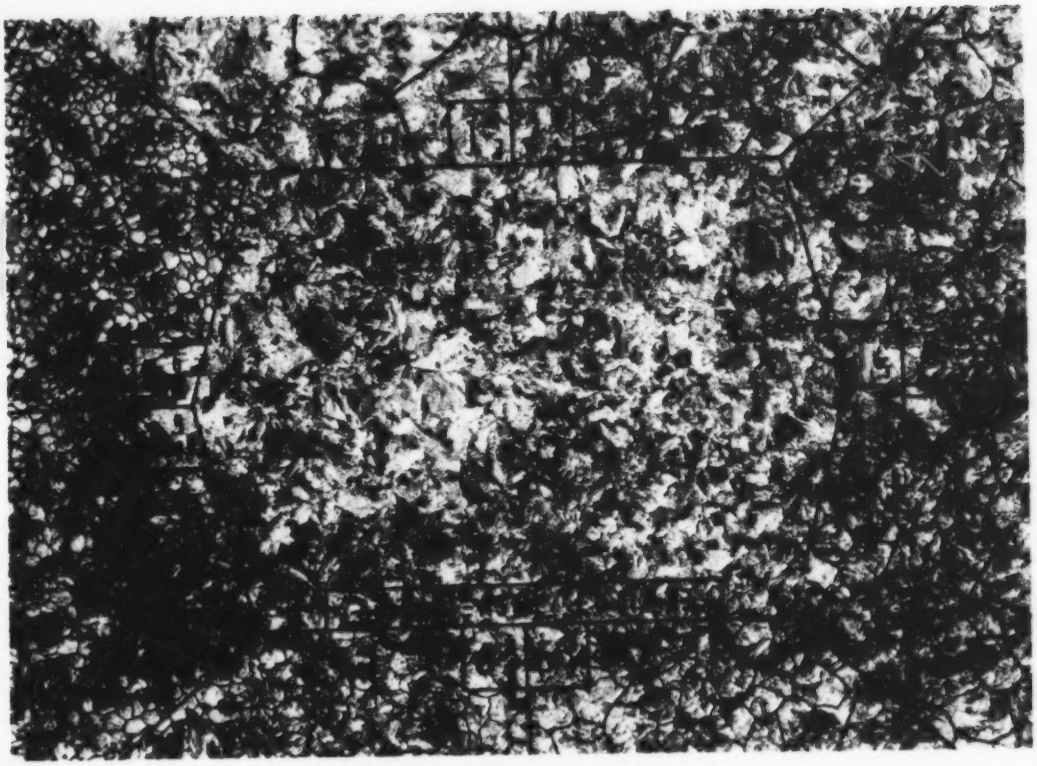


(a) X100. (neg 4486)

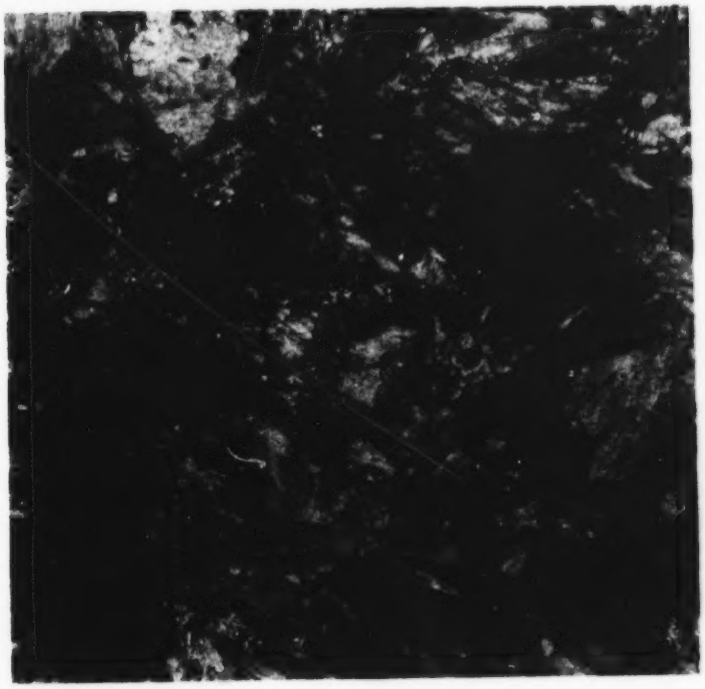


(b) Part of same area as (a). X500. (neg 4478)

Fig. 11. Sample 20, (heat 39808-20C). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 30).

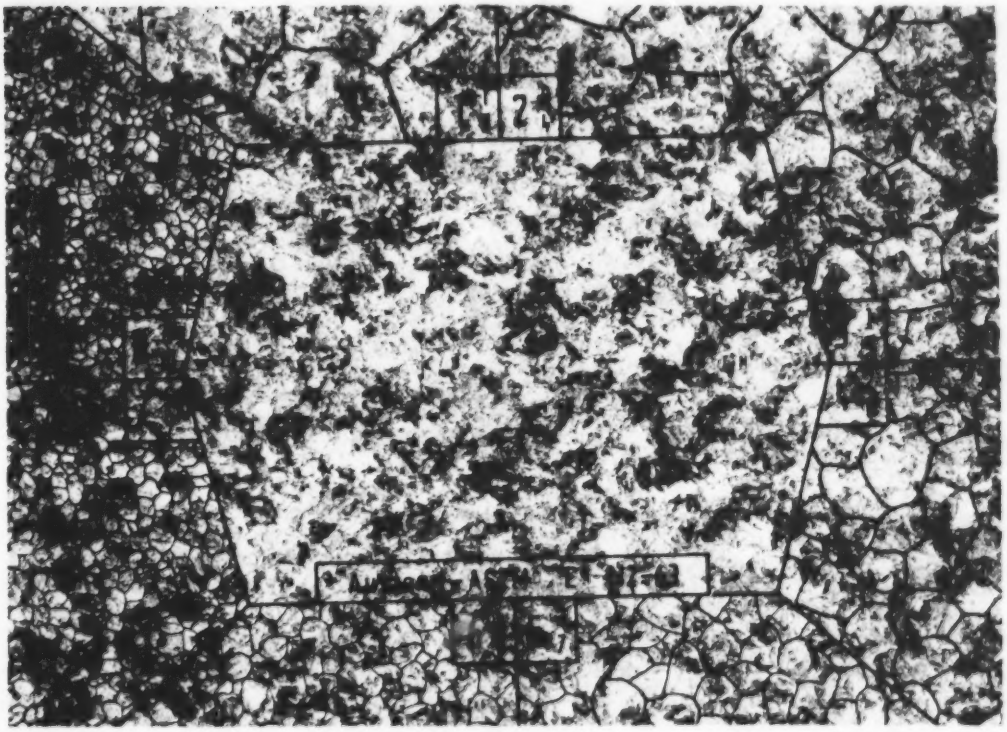


(a) X100. (neg 4487)



(b) Part of same area as (a). X500. (neg 4479)

Fig. 12. Sample 27, (heat 39762-27C). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 32).



(a) X100. (neg 4488)

(b) Part of same area as (a). X500. (neg 4480)

Fig. 13. Sample 28, (heat 39756-28C). Etched 10 s in boiling 4% picric acid-water. Cr-Cb rail. The ASTM E112 austenite grain size (a) = 4-6, (b) illustrates the prior austenite grain boundaries, (Rc 27).

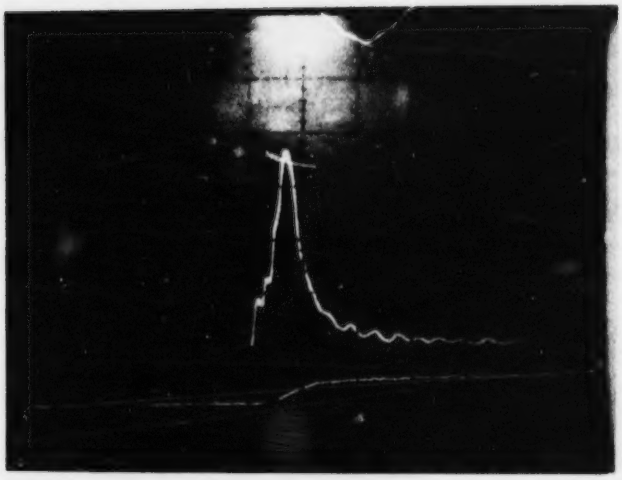


Fig 14a - 06H

(a) 06H (Heat 39406). Cr-Cb rail-head.
K_{Id}=25.6 MPa·$m^{\frac{1}{2}}$(23.3 ksi·$in.^{\frac{1}{2}}$).
P_{max} - 336 kg (740 lb).

load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4520)

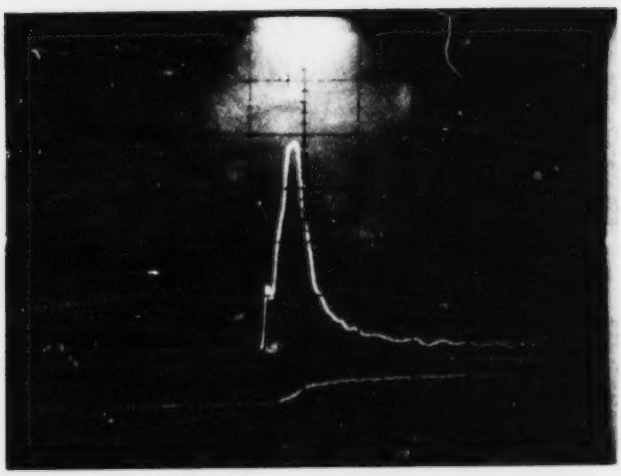


Fig 14(b) - 06W

(b) 06W (Heat 39406). Cr-Cb rail-web.
K_{Id}=26.7 MPa·$^{\frac{1}{2}}$(24.3 Ksi·$in.^{\frac{1}{2}}$)
P_{max} - 355 kg (780 lb)

load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4521)

Fig 14(c) - 06B

(c) 06B (heat 39406). Cr-Cb rail-base.
K_{Id}=25.6 MPa·$m^{\frac{1}{2}}$(23.3 ksi·$in.^{\frac{1}{2}}$)
P_{max} - 318 kg (700 lb)

load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4518)

Fig. 14. Instrumented precracked Charpy tests for dynamic fracture toughness.

Fig 15(a)-12B

(a) 12B (Heat 48791-12B)Cr-Cb rail-base.
K_{Id}=25.1 MPa·$m^{\frac{1}{2}}$(22.8 ksi·$in.^{\frac{1}{2}}$).
P_{max} - 318 kg (700 lb)
load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4519)

Fig 15(b)-80B

(b) 80B (Heat 48480). Cr-Cb rail-base.
K_{Id}=26.6 MPa·$m^{\frac{1}{2}}$(24.2 ksi·$in.^{\frac{1}{2}}$)
P_{max} - 427 kg (940 lb)
load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4516)

Fig 15(c)-04H

(c) 04H (Heat 48833-4C)Cr-Cb rail-head.
K_{Id}=23.2 MPa·$m^{\frac{1}{2}}$(21.1 ksi·$in.^{\frac{1}{2}}$)
P_{max} - 305 kg (671 lb)
load scale = 200 lb/div.
energy scale = 1 ft-lb/div.

(neg 4517)

Fig. 15. Instrumented precracked Charpy tests for dynamic fracture toughness.

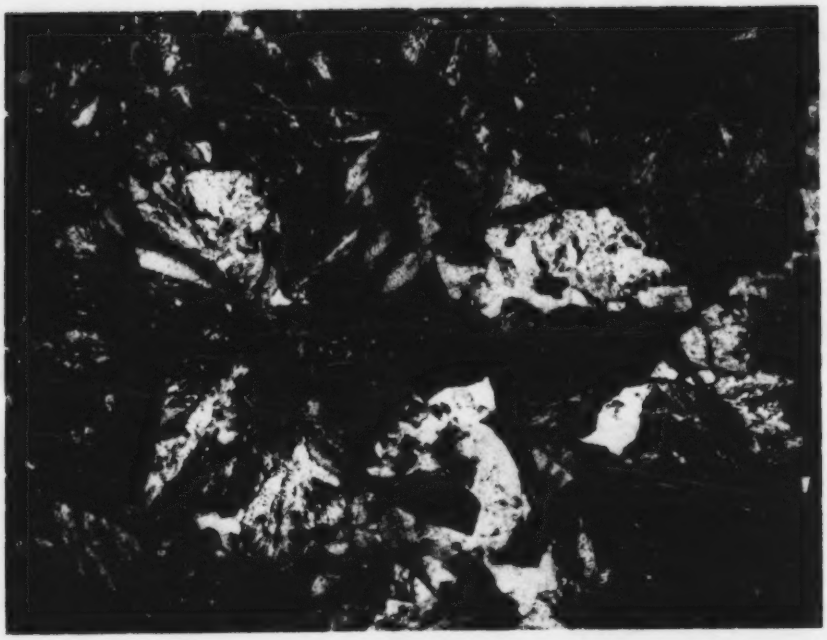


Fig. 16. Sample A. 1973 prototype rail (ASTM 6/8) Heat 14590. Etched 2% nital. X500 (Vacuum-degassed). (neg 428)

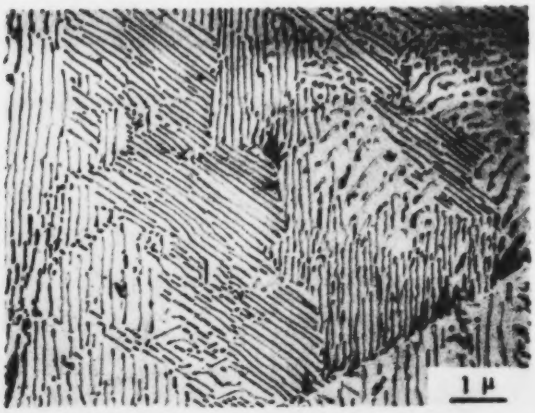


Fig. 17. Sample 48833-4C. (04). Electron micrographs of Cr-Cb rail samples. (neg 5152)

Fig. 18. Sample 48480. Showing Cb particle ≈ 0.3 μm. (80).
Electron micrographs of Cr-Cb rail samples. (neg 5151)

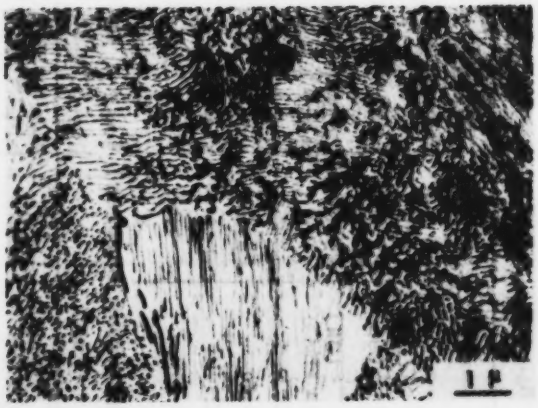


Fig. 19. Sample 48791-12B. Showing Cb particle ≈ 0.4 μm.
Electron micrographs of Cr-Cb rail samples. (neg 5153)

APPENDIX A

Fracture toughness, Cr-Cb rails - (1979 samples)

Cr-Cb Heat No.	Code	K_Q (ksi.in.$^{1/2}$)		K_{max} (ksi.in.$^{1/2}$)		K_{Id} (ksi.in.$^{1/2}$)		0.2% Tensile YS	Estimated critical flaw sizes calculated from K_Q for stress = 28.5 ksi	
		22°C	-50°C	22°C	-50°C	22°C	-50°C	(ksi)	d_c (in.)	d_c (mm)
48480	(80)	21.48	19.59	24.32	20.81	24.20	-	113	0.363	9.22
48791-12B	(12)	25.52	16.34	26.94	17.69	22.80	-	115	0.513	13.02
39406	(06)	27.00	22.04	29.61	24.14	23.63	-	113	0.573	14.57
48836	(04)	25.69	23.64	29.72	25.39	21.10	-	119	0.519	13.19
Av		24.9	20.4	27.7	22.0	22.9		115	0.488	12.40
Cr-Cb rails (1980 samples) (3)										
49078-CIA	(1)	25.60	21.26	27.15	22.61	-	-	-	0.516	13.10
48977	(2)	-	-	-	-	-	-	-	-	-
C17898	(3)	-	-	-	-	-	-	-	-	-
Cr-Cb 1973 prototype										
14590	(A)	27.56	-	34.13	-	-	-	110	0.598	15.18

APPENDIX A (cont'd)

Fracture toughness, carbon and alloy steel sections rails (4)

Type of rail	Code (4)	K_Q (ksi.in.$^{1/2}$)		K_{max} (ksi.in.$^{1/2}$)		K_{Id} (ksi.in.$^{1/2}$)		0.2% Tensile YS	Estimated critical flaw size (22°C), calculated from K_Q for stress = 28.5 ksi	
		22°C	-50°C	22°C	-50°C	22°C	-50°C	(ksi)	d_c(in.)	d_c(mm)
As-rolled C	P	30.80	21.20	39.90	21.20	-	-	87	0.747	18.97
Carbon QT	G,K	41.51	29.16	48.05	29.29	32.4	-	118	1.356	34.44
Cr-Mo (C5599)	B	36.40	28.80	41.50	31.90	34.7	-	118	1.043	26.49
1% Algoma Cr	R,D	32.95	23.90	39.22	24.80	-	-	106	0.855	21.70
1% BSC Cr	X	25.36	24.17	29.51	24.17	-	-	101	0.506	12.86
USSR P-65	P-65	42.51	31.07	46.12	37.80	33.70	24.00	118	1.422	36.13
Mn V-1965	Y	29.63	21.56	35.94	27.05	22.7	-	105	0.691	17.55
C-B-Al	3220	45.90	41.73	59.11	53.74	33.3	-	80	1.650	41.94
Cr-Mo (9273B)	W,Z	30.50	27.20	34.26	28.20	30.1	-	140***	0.730	18.50
Cr-Cb (1973)	A	27.56	23.0*	34.13	28.5**	-	-	110	0.598	15.18

$$d_c = \frac{2}{\pi}\left(\frac{K_{Ic}}{\sigma \text{ applied}}\right)^2 \quad (6).$$

*A K_Q(-200°C) = 16.1 MPa·m$^{1/2}$ (14.66 ksi·in.$^{1/2}$) [Interpolated at -50°C to obtain 27.6 MPa·m$^{1/2}$ (23.0 ksi·in.$^{1/2}$) for K_Q -50°C (A)]

**A K_{max}(-200°C) = 19.6 MPa·m$^{1/2}$ (17.82 ksi·in.$^{1/2}$) [Interpolated at -50°C to obtain 34.1 MPa·m$^{1/2}$ (28.5 ksi·in.$^{1/2}$) for K_{max} -50°C (A)]

***Bainitic microstructure A_{r_3} = 660°C (1220°F)

APPENDIX B

(Cr-Cb) Mn-Mb-Cr - Sample (A)* Heat 14590 (1973)
Table B3 (11)

Test			Stress intensity, pop-in and break fracture-toughness test data/ASTM E399-74								Tensile data		Impact data			
									Load				Charpy U (ft-lb)		Charpy V (ft-lb)	
Bar No.	Test temp °C	Type of test	$K_{Ic}(K_Q)$ (psi.in.)	K break (psi.in.)	a (in.)	$\frac{a}{W}$ (in.)	$f\left(\frac{a}{W}\right)$	Fatigue crack length (in)	pop-in (lb)	Break (lb)	0.2% YS (ksi)	RA (%)	-40°C	-18°C	-40°C	+24°C
A3	24	WOL	29500	35600	0.437	0.518	10.14	0.094	2000 [15]	2415	110	30	14	91	-	?
A4	"	"	27200	34040	0.468	0.554	11.26	0.125	1660 [10]	2080	"	"	"	"	-	"
A5	"	"	24400	33610	0.484	0.573	12.30	0.141	1365 [5]	1880	"	"	"	"	-	"
A6	"	"	25040	35510	0.468	0.554	11.26	0.125	1530 [10]	2170	"	"	"	"	-	"
A7*	"	"	24400	31750	0.468	0.554	11.26	0.125	1490 [8]	1940	"	"	"	"	-	"
A8*	"	"	35220	35370	0.437	0.518	10.14	0.094	2390 [60]	2400	"	"	"	"	-	"
A1	-200	WOL	13575	16400	0.468	0.555	11.46	0.125	815 [-1]	1005	-	-	-	-	-	-
A2	"	"	15750	18900	0.484	0.573	12.30	0.141	880 [-1]	1060	-	-	-	-	-	-
A2	24	CT	29890	36250	0.640	0.640	16.04	0.140	930 [-1]	1130	110	30	14	91	-	?
A5	"	"	26900	33600	0.593	0.593	16.17	0.093	1020 [-1]	1275	"	"	"	"	"	"
A7	"	"	28070	34485	0.687	0.687	20.05	0.187	700 [-1]	860	"	"	"	"	"	"
A8	"	"	34250	34250	0.593	0.593	13.17	0.094	Nil	1300	"	"	"	"	"	"
A10	"	"	21180	31000	0.562	0.562	11.74	0.063	900 [-1]	1320	"	"	"	"	"	"

*Sample A - MRP/PMRL-77-4 (R)
*Longitudinal notches in WOL bars 7 and 8
WOL - Manjoine test bars (Dwg. 1813) - ASTM E399-74
CT - Compact tension bars (Dwg. 1812) - ASTM E399-74
[ ] load-drop (lb)

$K_{WOL} = \frac{p}{0.689.} f\left(\frac{a}{W}\right)$ B = 0.75 in. w = 0.844 in.

$K_Q = 2p. \quad f\left(\frac{a}{W}\right)$ B = 0.5 in. w = 1.0 in.

$d_c = \frac{2}{\pi}\left(\frac{K_{Ic}}{\sigma \text{ applied}}\right)^2$

Conversion factors
1 ksi (kpsi) = 6.895 MPa
1 in. = 25.4 mm
1 lb = 0.455 kg
1 ksi.in.$^{1/2}$ = 1.100 MPa.m$^{1/2}$
1 ft-lb = 1.356 Joules

APPENDIX C

Table 14. Summary of yield strength, hardness and toughness properties. Average values (9).

Sample code	YS (0.2%) (ksi)	Stress intensity K_{Ic} psi.in.		Hardness Rc	Charpy unnotched ft-lb	Charpy unnotched ft-lb	Charpy V-notch ft-lb	Critical crack size* d_c		Tensile ductility RA (%)	Stress intensity K_B psi.in.$^{1/2}$		Sample description
		K_{Ic}*	K_{Ic}(sd)		-40°F (-40°C)	0°F (-18°C)	75°F (24°C)	in.	mm		K_B max	K_B (sd)	
X**	101	25359	(1951)	35	15	49	2	0.502	12.75	20	29511	(2656)	BSC Heat 16102-E (1.2% Cr)
14590 A	110	27557	(4318)	38	14	91	2[1/2]	0.593	15.06	30	34133	(1620)	Mn-Mb-Cr, 14590, SYSCO AP
W	164	29838	(2781)	40/46	14	21	5[2/9]	0.695	17.66	35	37585	(1668)	Cr-Mo, 9273B, TDA/77 AP
P	87	30797	(5978)	28	7	15	2[2/3]	0.741	18.82	17	39808	(4069)	Carbon steel, Algoma, AR, cc/1978
R**	106	32948	(4676)	35	35	39	3	0.848	21.54	13	39216	(5735)	1.4% Cr, Algoma, AR, cc/76
20	119	34340	(2824)	38	127	140	-	0.921	23.39	33	41950	(2719)	Cr-Mo, C5509, TDA, 1975 Rail 20 AP
19	111	36803	(10839)	38	67	147	-	1.058	26.87	32	54543	(10420)	Cr-Mo, C5599, TDA, 1975 Rail 19 AP
G	-	37293	(6239)	38	142	167	-	1.086	27.59	30	40817	(6136)	Carbon steel, OT, CPP
B	115	38748	(9296)	38/43	88	140	-	1.173	29.79	33	49436	(8018)	Cr-Mo, C5500, Av., tests 17, 19, 20
D	-	39697	(6105)	35	-	-	-	1.231	31.26	-	41048	(5135)	1.2% Cr, Algoma AP, cc/70
K	118	41510	(6008)	38	148	148	7[7/8]	1.346	34.18	25	48050	(11385)	Beth., Steelton, OT, carbon, 1976
17	118	47867	(7438)	42	70	133	4[2/6]	1.790	45.45	33	50903	(5351)	Cr-Mo, C5500, TDA, 1975, Rail 17, AP
V	-	49432	(9515)	28	-	-	-	1.908	48.48	-	62793	(10651)	C-B-Al, Carbon steel AP, SYSCO 2220

*at 24°C; ( ) standard deviation; [ ] range of values; **tensile ductility and unnotched impact strength are relatively low.

*critical crack size $d_c = \frac{2}{\pi}\left(\frac{K_{Ic}}{\sigma_{app}}\right)^2$ in; σ_{app} = 28.55 ksi (196 MPa); K_{Ic} = 44.9 ksi.in.$^{1/2}$ (49.4 MPa·m$^{1/2}$) for as-rolled C steel: d_c = 1.57 in. = 40 mm (ref. 5) for as-rolled carbon steel

K_{Ic} determined by compact tension and WOL test according to ASTM E399-74. K_{Ic} from pop-in.; $K_B = K_{max}$ from breaking load.